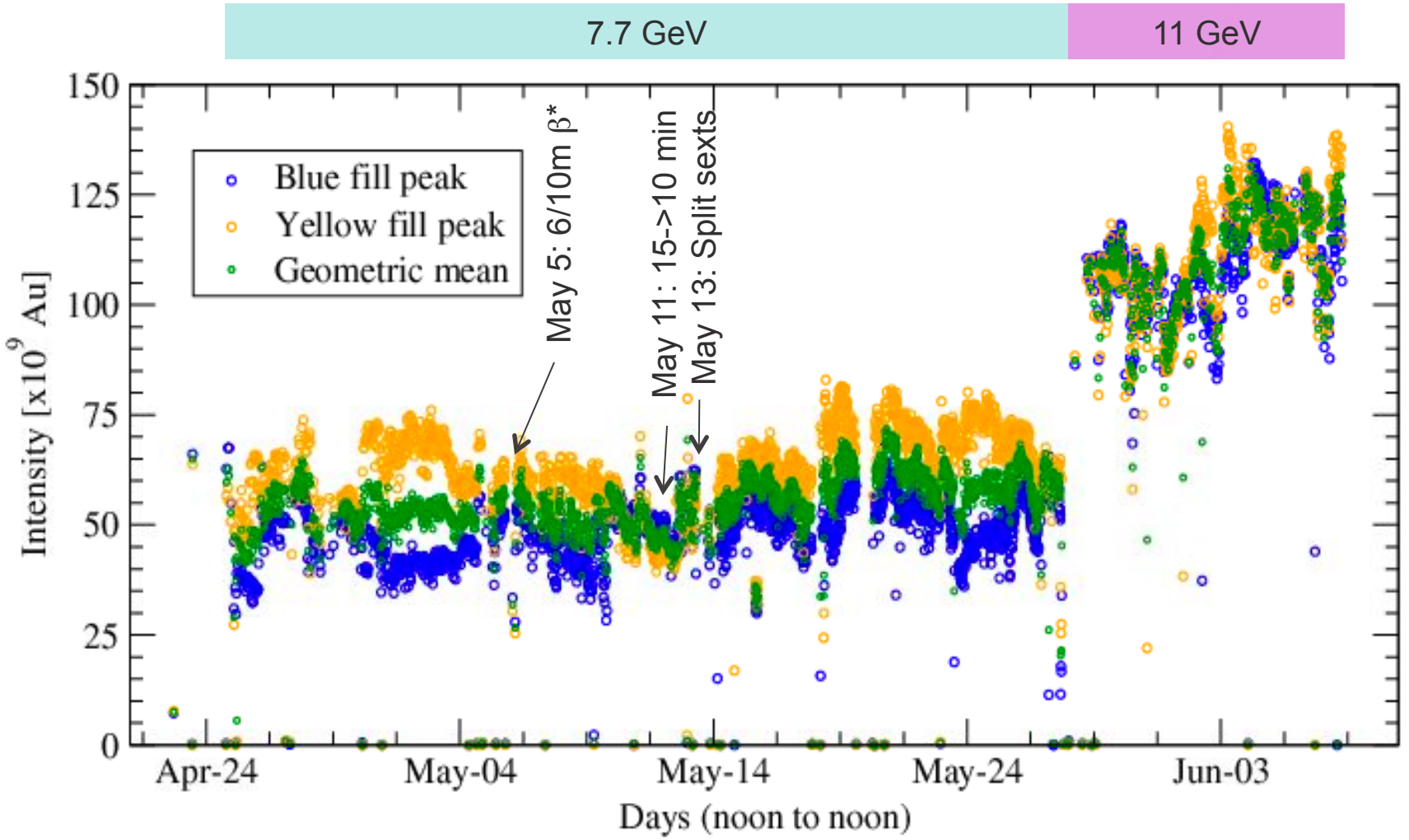
Retrospective of RHIC Low Energy 2010

$\sqrt{s_{NN}}$ [GeV]	Start date	End date	# Days
200	Dec 5 2009	Mar 18	103
62.4	Mar 18	Apr 9	22
39	Apr 9	Apr 22	13
7.7	Apr 22	May 27	35
11.5	May 27	Jun 7	11
5 (test)	Jun 7	Jun 9	2.5

- Just what is "low energy"? Some confusion!
  - STAR BUP BES (beam energy scan): up to $\sqrt{s_{NN}}$=39 GeV
  - C-AD "low" = below injection: up to $\sqrt{s_{NN}}$=20 GeV
- A mix of where we were and lessons learned
  - Even though we may not run at these energies again

General Comments: Intensity History

STAR collisions only



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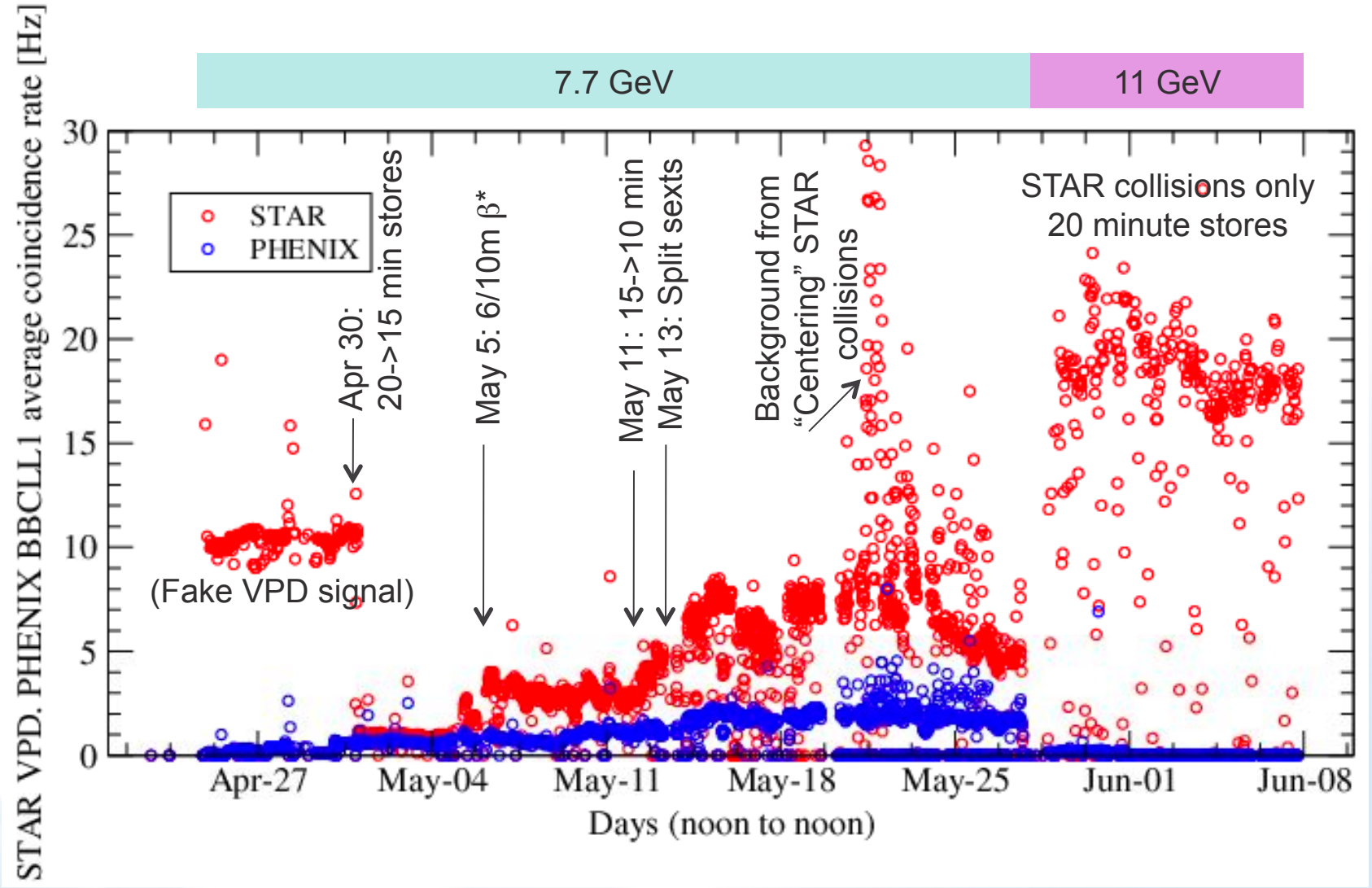
General Comments: "Luminosity" History



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General Comments: "Luminosity"

- Scaler/trigger changes made luminosity counting tough
  - Understandable in a background-rich short run
  - Emphasis on # of good events rather than integrated lumi
  - Short runs/config made luminosity counting hard for pfi/lla
    - Reconciling logged data in the future will be challenging
    - BUT clean counters were also critical to success of run!
- STAR rate roughly scaled as γ^3: $(6.18/4.14)^3=3.33\sim20/6$
  - Consistent with previous experience
  - This scaling clearly does NOT hold down to 5 GeV
- Recommendations
  - Integrated lumi program should be configurable
  - Use only raw logged scaler channels
  - Require detailed documentation of experiment scaler configuration changes

General Comments: Magnetic Measurements

- Dipole/quad cold measurements from Animesh Jain
- Reduce main dipole b2, lattice nonlinearity

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I hope it will be much simpler to just try a cycle to ~350-400A with
down ramp operation directly in RHIC.  Even if you do not hit
exactly zero, you should get at least a factor of 2-3 reduction in
b2.

- Animesh
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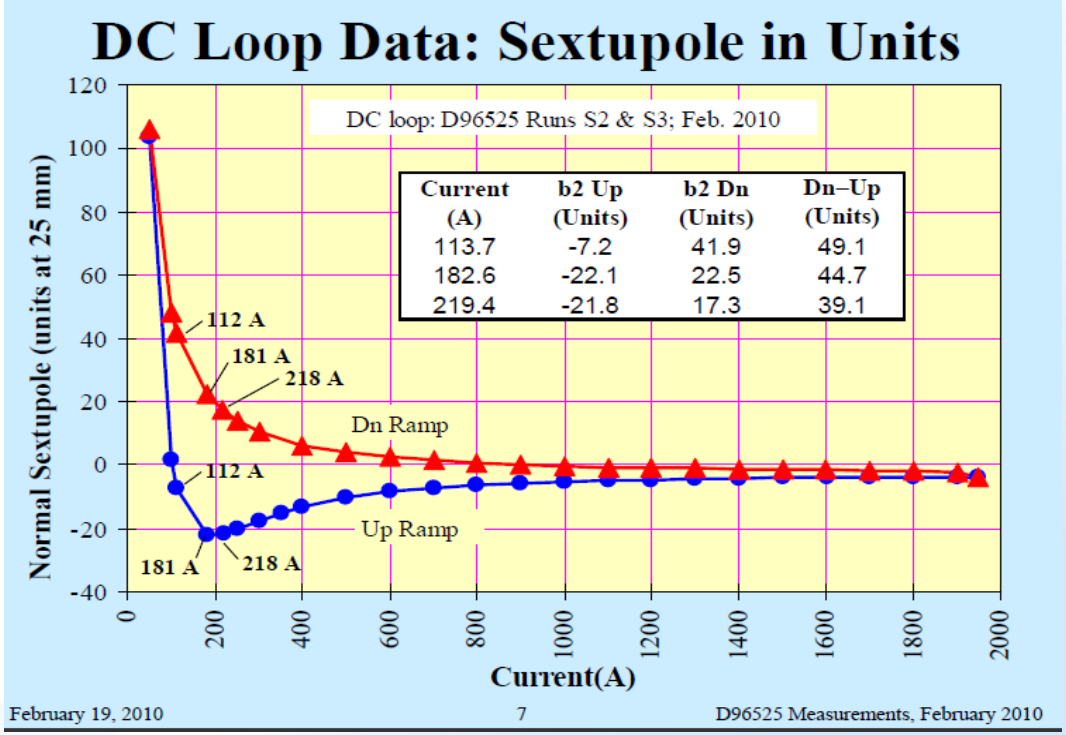
- Did not use this data effectively
  - No tracking
  - Up/down ramp confusion
    - Design ramps with optimal nonlinearity tradeoffs for future
  - More measurements?

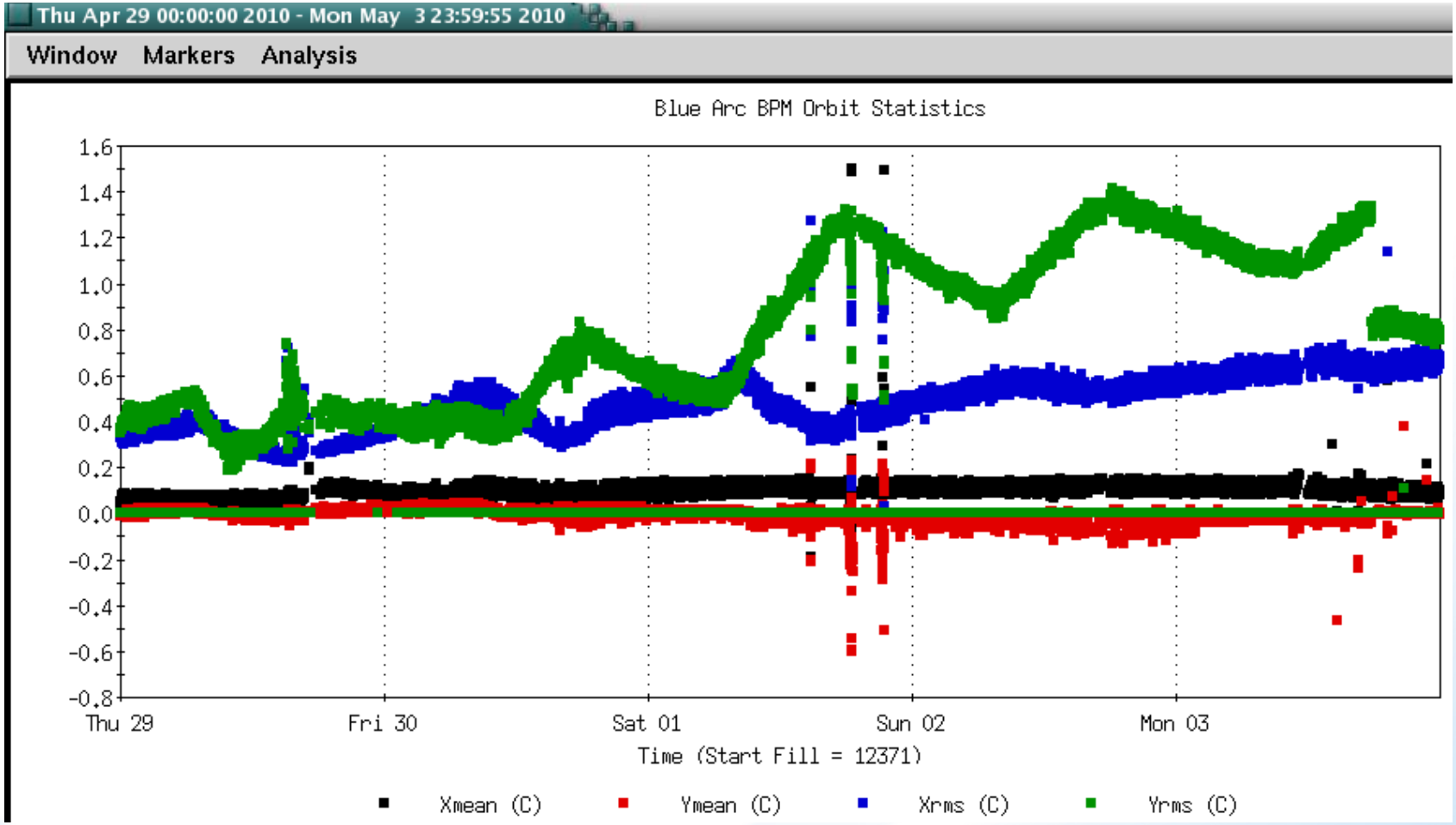


General Comments: Collimation

- Injecting with collimators in was also critical for success
  - Permitted experiments to stay on even at lowest energy
  - Localized injection losses
  - Gave PHENIX clean enough conditions to run at all
  - Gave STAR clean enough conditions to improve triggers

- Collimators needed constant caretaking
  - Angelika was often retuning collimators
    - Even small changes become very significant when collimators are pushed in to a few beam sigma
  - Becomes an orbit correction disincentive (oddly enough)
    - Which also has some benefits…

General Comments: Orbit Data Mining



- Days of many orbits with very few machine changes
  - Great statistics to evaluate details of magnet/thermal drift

$\sqrt{s_{NN}}$=7.7 GeV: Challenges

- Losses and loss management
  - Monitoring of chronic loss accumulation through run
  - Permitted 20 min to 15 min to 10 min store lengths
  - Weekly report to RSC, daily vigilance by run coordinator
  - There will be an AP note documenting low energy losses
- Beta squeeze, β^*=10m to 6m in STAR
  - Tried PHENIX too, but failed to understand backgrounds
  - Both improvements gave at least x4 lumi improvement
- Injection efficiency limited by pitching/coll/abort losses
  - U to X/Y transformer efficiencies: 90-95%
  - But calibrations about transformer calibrations…
- Many small difficulties overcome
  - Orbit correction, gap cleaning, chrom control, collimation…

$\sqrt{s_{NN}}$=7.7 GeV: Loss Management

- Loss management was critical to the success of 7.7 GeV
  - Thanks to Dana Beavis / RSC
  - Thanks to BLM folks for extra BLMs around RHIC injection
- Wrote log analysis scripts to evaluate/correlate/integrate BLM losses
  - Prioritized, flagged outliers
  - ~90% of losses in capped areas of abort/collimators/ lambertsons
- Dominated by ATR losses
- Documentation (AP note) is a post-run deliverable

Table 1: Low energy losses tabulated by total losses and number fills, for fills 12594-13607, sqrt(sNN)=7.7 GeV.

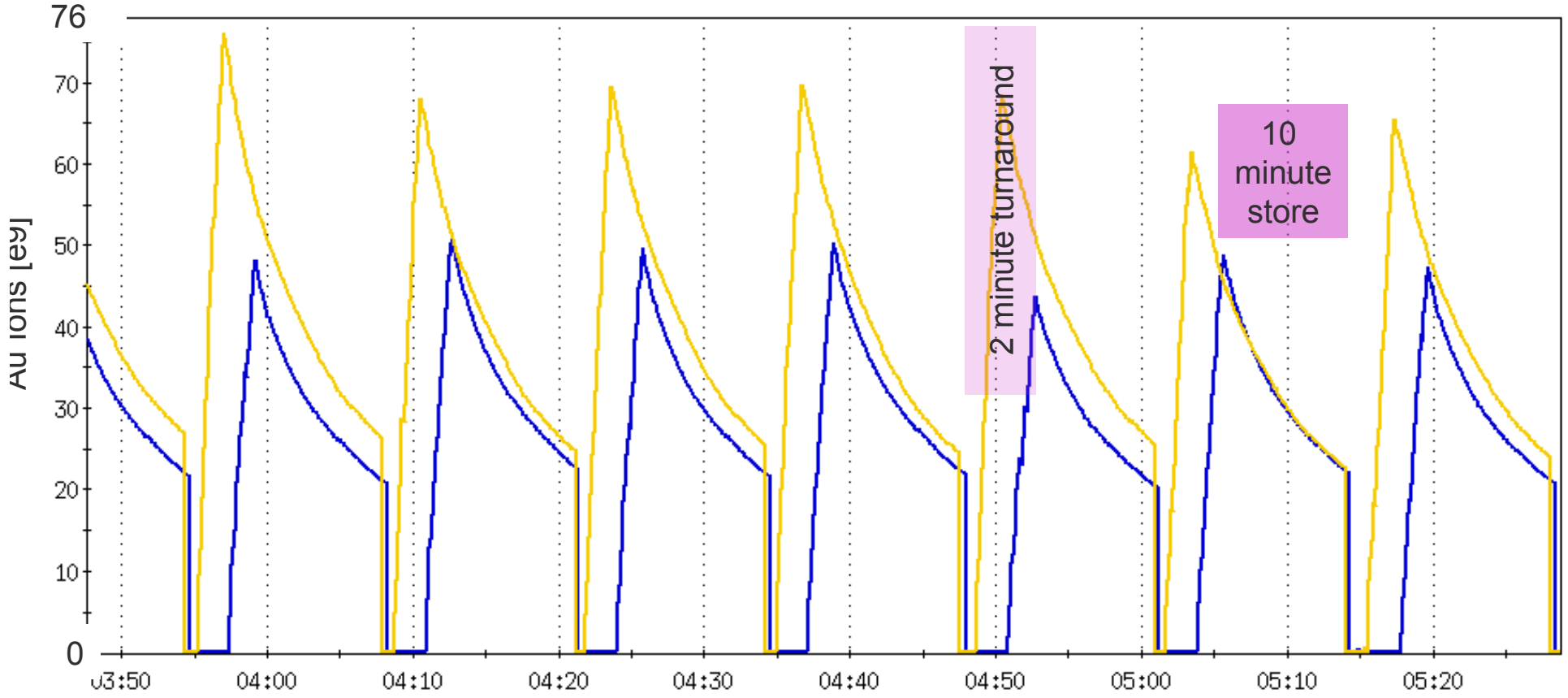
Num	%TotLosses	Total/Avg Losses	SWN
997	36.2+/-13.2	99.71+/- 146.2	y7-lm3.2-c
1008	15.2+/- 7.8	5.27+/- 64.6	b10-lm3.5-dmp
999	13.9+/- 9.0	114.06+/- 314.2	b8-lm3.2-c
1005	8.8+/- 3.3	17.50+/- 203.6	y9-lm3.5-dmp
830	8.0+/- 8.5	40.71+/- 256.7	y9-lm3.7-dmp
959	6.1+/- 2.0	111.93+/- 244.8	y7-lm3.4-c
799	2.9+/- 1.2	122.06+/- 115.7	b8-lm3.4-c
734	2.6+/- 3.1	75.16+/- 363.8	b6-lm11-atr
476	2.3+/- 2.9	99.36+/- 475.0	b6-lm10-atr
128	1.6+/- 1.1	170.48+/- 888.7	b9-lm3.6-dmp
96	8.8+/-15.1	434.86+/- 637.5	g7-mlmx.1
48	2.5+/- 3.0	352.45+/-1019.0	b10-lm3.7-dmp
32	2.3+/- 1.7	471.05+/-1103.2	b10-lm3.9
31	4.2+/- 4.9	1273.73+/-2200.4	y7-lm3.2
31	2.5+/- 2.3	838.40+/-1835.5	y9-lm4
28	4.0+/- 7.9	1278.67+/-1531.2	b6-lm-lamb
22	4.7+/- 7.8	738.70+/-1328.6	b10-lm4
21	2.2+/- 1.6	880.62+/- 955.3	g9-lm5
21	2.0+/- 1.2	210.77+/- 739.0	y10-lm3.6-dmp
20	2.6+/- 2.1	2026.33+/-1911.9	b10-lm3.3-ka
19	2.9+/- 3.6	990.01+/-1734.2	b9-lm4
19	2.8+/- 2.0	1124.10+/-1360.3	y9-lm3.3-ka
18	2.5+/- 1.9	632.17+/-1026.9	y10-lm4
17	2.2+/- 2.1	699.81+/- 999.5	b6-lm3.2
16	2.1+/- 1.3	1513.97+/-1228.7	b10-lm3.4-ka
15	3.8+/- 4.1	1750.21+/-2319.0	b10-lm3.2-ka
14	2.3+/- 1.4	1438.46+/-1743.0	y9-lm3.4-ka
13	3.0+/- 2.7	2357.14+/-2502.1	y9-lm3.2-ka

$\sqrt{s_{NN}}$=7.7 GeV: Beta Squeeze

- Thanks to Dejan for pushing a "crazy" idea
  - In retrospect not so crazy after all
  - Nearly doubled luminosity at STAR

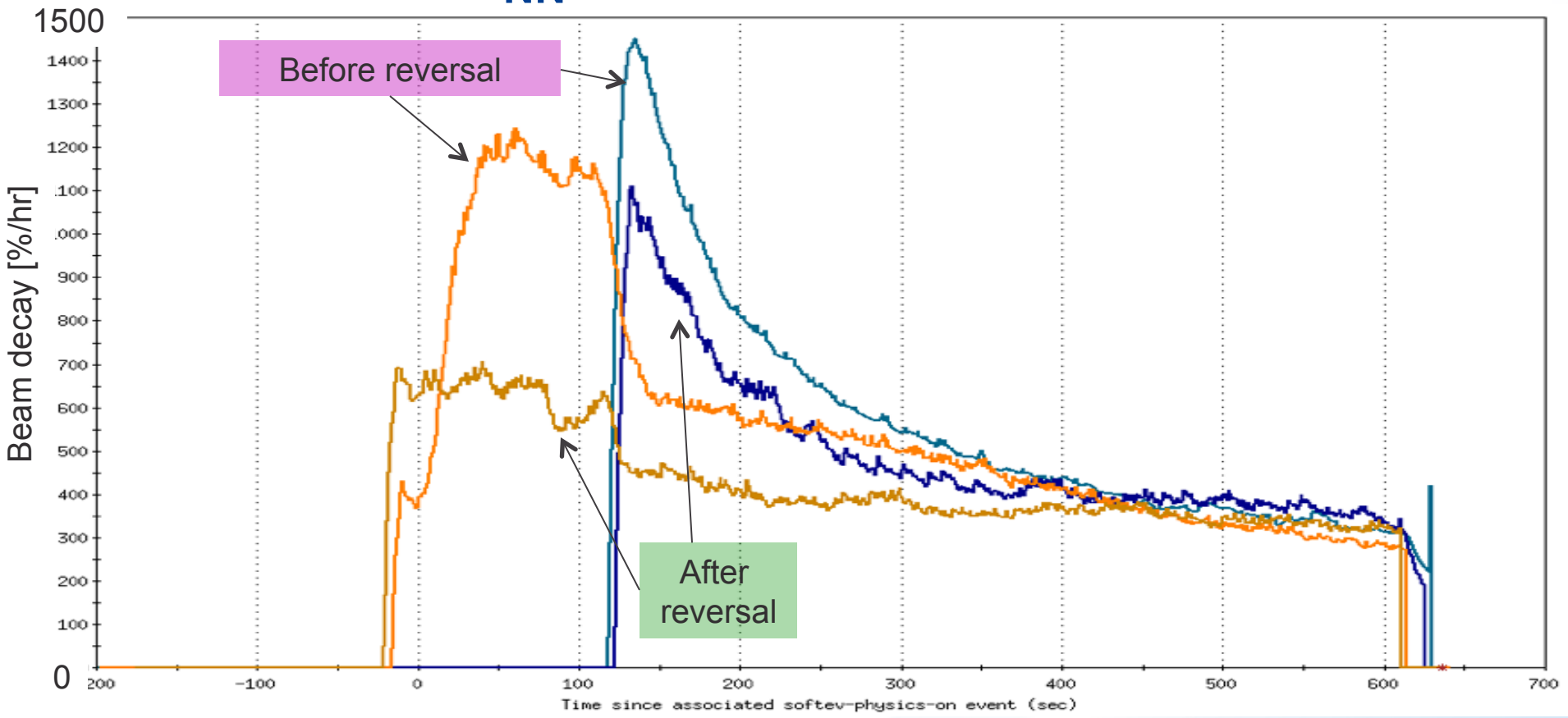
- But I think we (or rather I) got lucky
  - Squeeze created significantly more scattering background
    - A lot of these can't be collimated
    - Have to count on experiments to have a way to reject them
  - PHENIX doesn't have good enough vertex reconstruction resolution to reject beam-beampipe backgrounds
    - Did not understand this until well into beta squeeze study
  - Fortunately STAR did
    - Hence 6m/6m squeeze didn't work (killed PHENIX)
    - But 6m/10m squeeze did

$\sqrt{s_{NN}}$=7.7 GeV: Keeping Operations Busy



- Operations was superlative with very fast turnarounds
  - Time in physics was often 80%, ~2 minute turnarounds
  - Very close to optimal given lifetime and tuning conditions

$\sqrt{s_{NN}}$=7.7 GeV: Sextupole Reversal



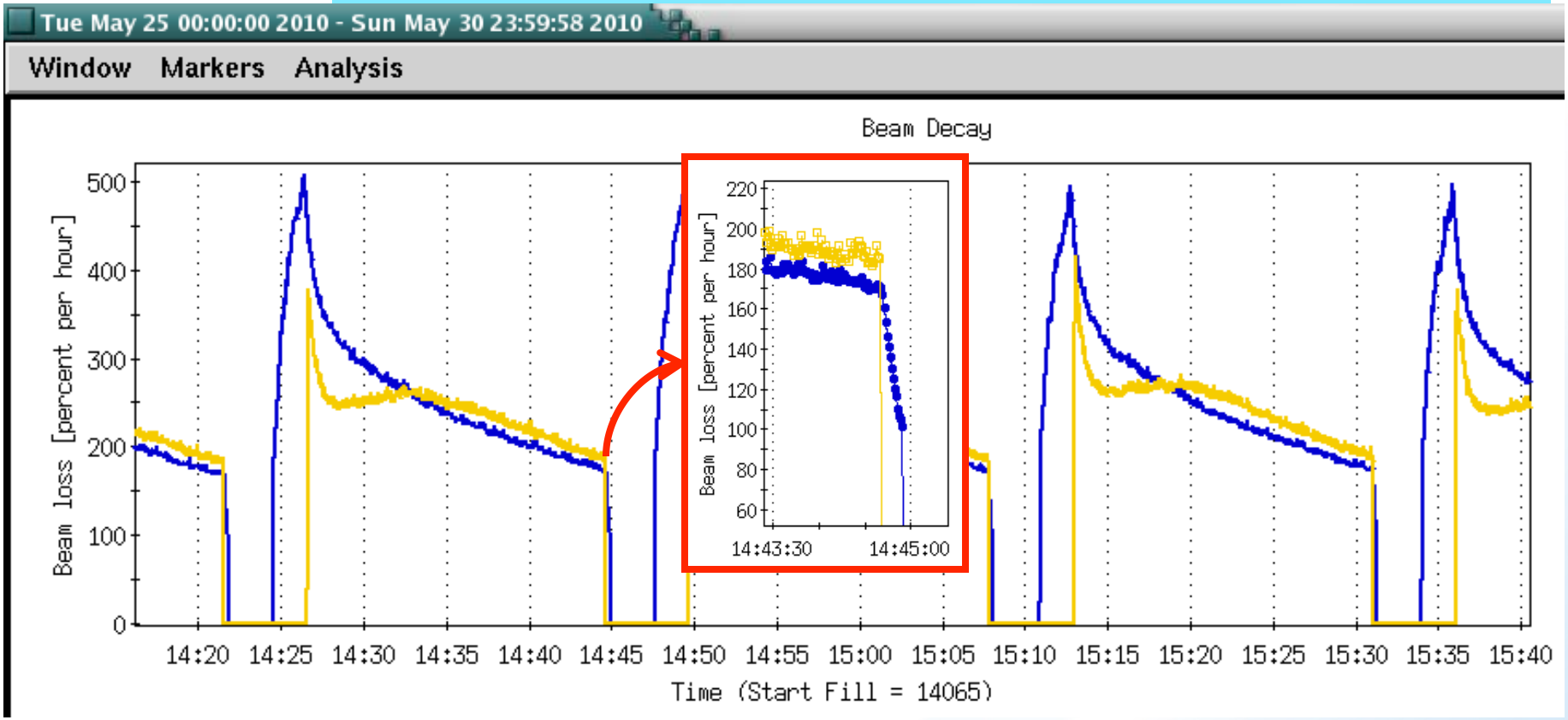
- Reversing half of sextupole families = "bipolar" sextupoles
- Beam decay significantly improved by adjusting chroms
- ~30% improvement in integrated luminosity
- Difficult to predict: sextupole currents are <1A

$\sqrt{s_{NN}}$= 11.5 GeV: Comments

- Many thanks to Greg, Angelika, and Vincent
  - Greg was the real run coordinator for this run
  - About 16h to physics from beam setup start
  - Some evidence of instabilities with high beam currents
  - Store length rapidly shortened to 1h, then 20 minutes
  - A challenge to cog to STAR collisions properly with h=363

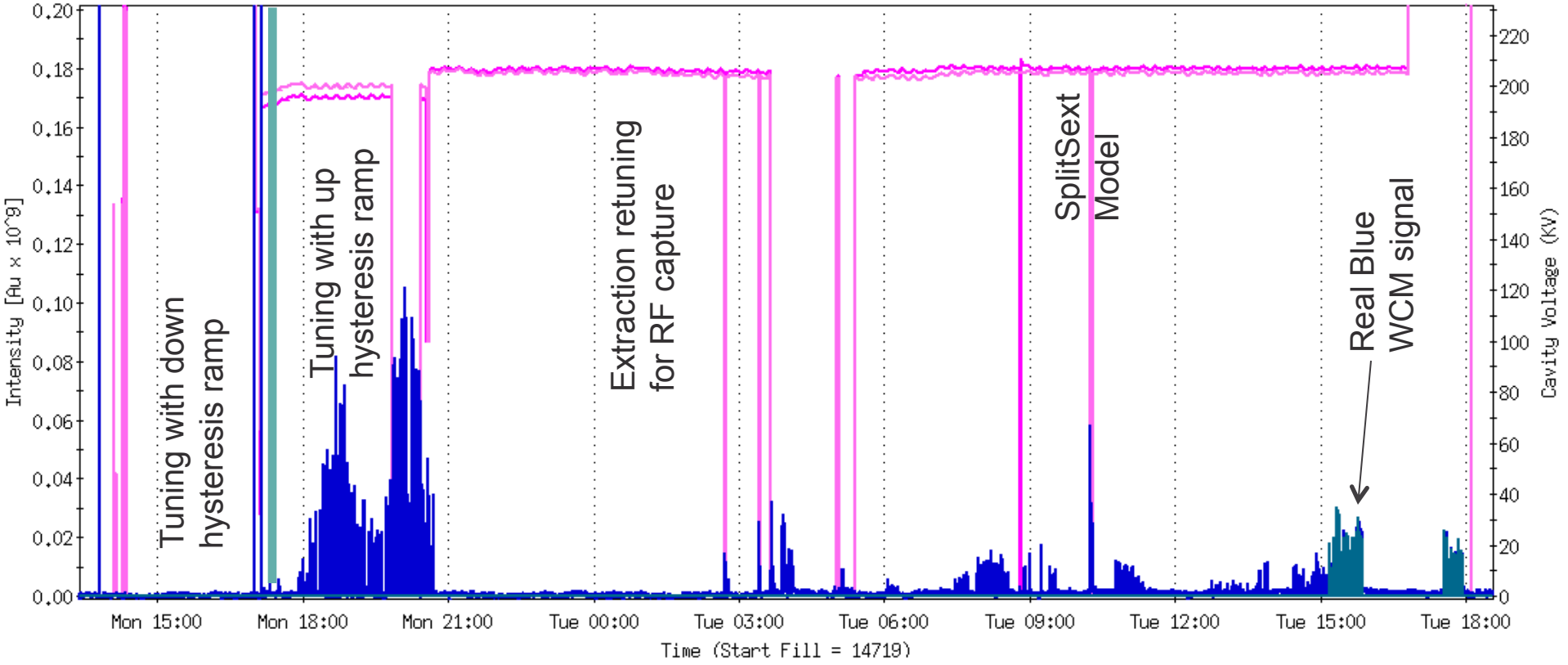
- A big success, almost clockwork
  - Easier after 7.7 GeV challenges
  - Benefitted from “bipolar” sextupole configuration, no switch
  - Beam decay down a factor of ~4, intensity up x2.5

$\sqrt{s_{NN}}$= 11.5 GeV: Beam-Beam



- 11.5 GeV routinely showed strong beam-beam signatures
  - Beam decay improvement at when colliding beam dumped
  - Unexpected for single head-on collision: parasitic collisions?

$\sqrt{s_{NN}}$= 5 GeV/u Blue Beam Currents



- Some limited blue beam seen on blue WCM! (2.5e7)
- Peak DCCT 1.1e8 unbunched, 8e7 “bunched”, 2e7 bunched
- Blue final lifetimes: 4s(65%)/40s(35%), peak 2e7

$\sqrt{s_{NN}}$= 5 GeV: Some Lessons Learned

- Hysteresis for up ramp created several problems
  - Turned synchro off (AGS U2 instead of U1)
  - Turned RF cavities on, unnoticed for 2 hours!
  - Corollary: downramp test requires new fieldfits in ramp
- RF capture was much harder than expected
  - Neglected energy loss (~1%?) from stripping foil
    - 2.9 kHz (1e-4 df/f) off frequency in RHIC!
  - Chased tails with AGS/RHIC configurations (+15mm bump!)
  - Final solution sacrificed AGS/ATR to maintain RHIC
    - Leftover concerns from downramp transfer function issues?
- Chromatic control was not consistent early in test
  - Proper split sextupole model installed Tuesday morning
  - Much better chromaticity tuning behavior afterwards

$\sqrt{s_{NN}}$= 5 GeV: Some More Lessons Learned

- It's very hard to tune beam that has…
  - 10-30 turns of longitudinal decoherence with RF off
  - 10-30 turns of transverse decoherence with RF on
  - basically no bunched beam lifetime, limited BPMs
  - Intensity, intensity, intensity
- Chromaticity model is particularly important
  - Decoherence and momentum aperture are challenging
  - Starting in vaguely the right place would help
  - Bucket dp/p 1e-3; should be able to scan 5-10 chrom units
  - Looked like machine was dominated by nonlinearities
    - A show-stopper for cooling at this energy if true
- Aperture was always in the abort area
  - Study details of longitudinal and transverse apertures

General Comments: Great Support!!

- LLRF for figuring out how to avoid blue cogging glitches
  - Allowed PHENIX to run continuously => 10 min stores
- LLRF/Instrumentation for harmonic number support
  - Danced through several harmonic numbers (363, 366, 387)
- Vincent for ATR loss vigilance
  - ATR losses were limiting radiological issue for low energy
- Angelika for collimator vigilance
  - Aggressive collimation was required for entire run
- Operations for weeks of 2 minute turnarounds
- Greg for 11.5 GeV coordination
- Everyone for all the support that made low energy (and in particular 7.7 GeV) such a success

Low Energy Parameters

	Au nom injection	Au 2007-8	Au 2008/10	Au 2010	Au 2010
$\sqrt{s_{NN}}$ [GeV]	19.6	9.18	5.0	7.7	11.5
Baryochemical potential μ_B [MeV]	197	360	535	405	305
Beam energy [GeV/u]	9.8	4.59	2.5	3.85	5.75
Beam kinetic energy [GeV/u]	8.87	3.66	1.57	2.92	4.82
Relativistic γ	10.53	4.93	2.68	4.14	6.18
Relativistic β	0.995	0.979	0.928	0.970	0.987
Momentum [GeV/c]	9.76	4.50	2.32	3.736	5.674
Rigidity Bρ [T-m]	81.15	37.40	**19.30**	**31.07**	**47.20**
RF harmonic number	360	**366**	387	369	**363**
RF frequency [MHz]	28.1	28.03	28.08	28.00	28.01
Max beam size (95%) $\hat{\sigma}$ [mm]	10.48	15.32	**21.32**	**16.81**	**13.64**
Beam/ring time available	--	27/30.5h	(1-2d?)	4wks	(2wks)
Luminosity [x10^{23} cm^{-2} s^{-1}]	(20-80)	1.2-3.5	--	(~10)	(~30)

RHIC full aperture at β_{max} is 113 mm; at 7.7 GeV this is ±3.3 σ_{max}(95%)

(μ_B from Andronic, Braun-Munzinger, Stachel, Nucl Phys A 772, 2006)

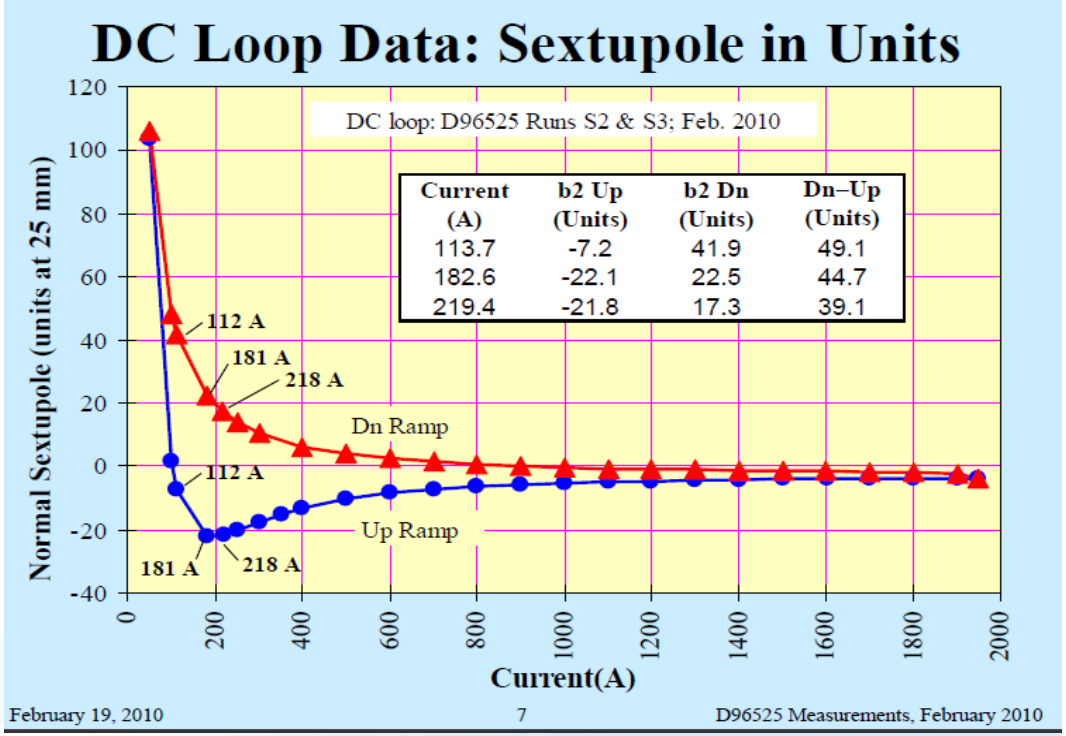
E=2.5 GeV/u Downramp Hysteresis

- Suggested in discussions with Alexei, Animesh Jain
- Objective is to reduce main dipole b2, lattice nonlinearity

I hope it will be much simpler to just try a cycle to ~350-400A with down ramp operation directly in RHIC. Even if you do not hit exactly zero, you should get at least a factor of 2-3 reduction in b2.

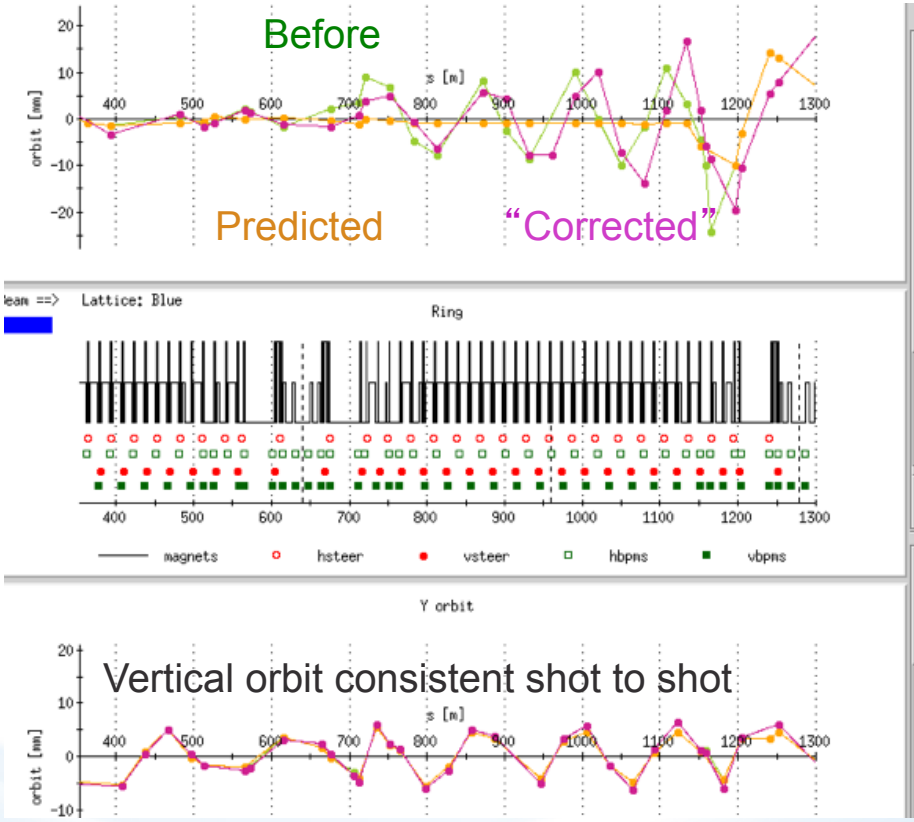
- Animesh

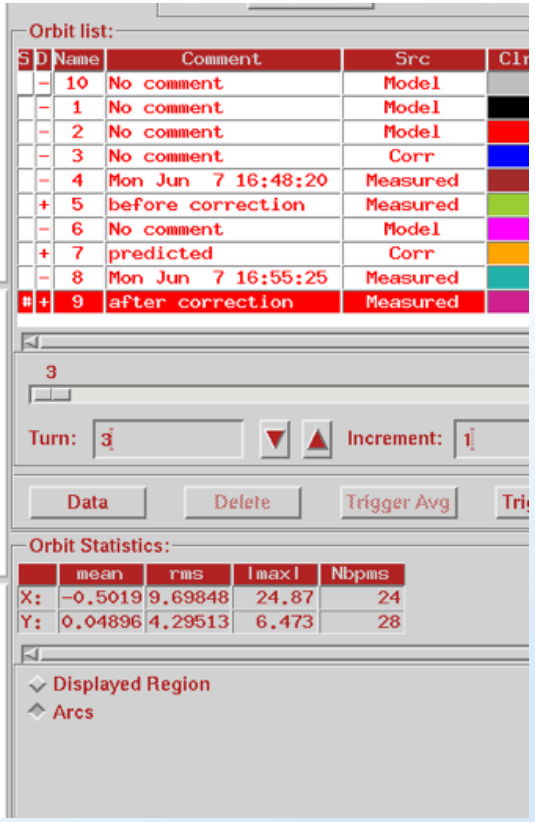
- But neglected dipole, quad transfer matrix changes of ~1% (!!)
- Clearly observed in bad tunes, radius
- Rescaling strengths was perceived to be time prohibitive



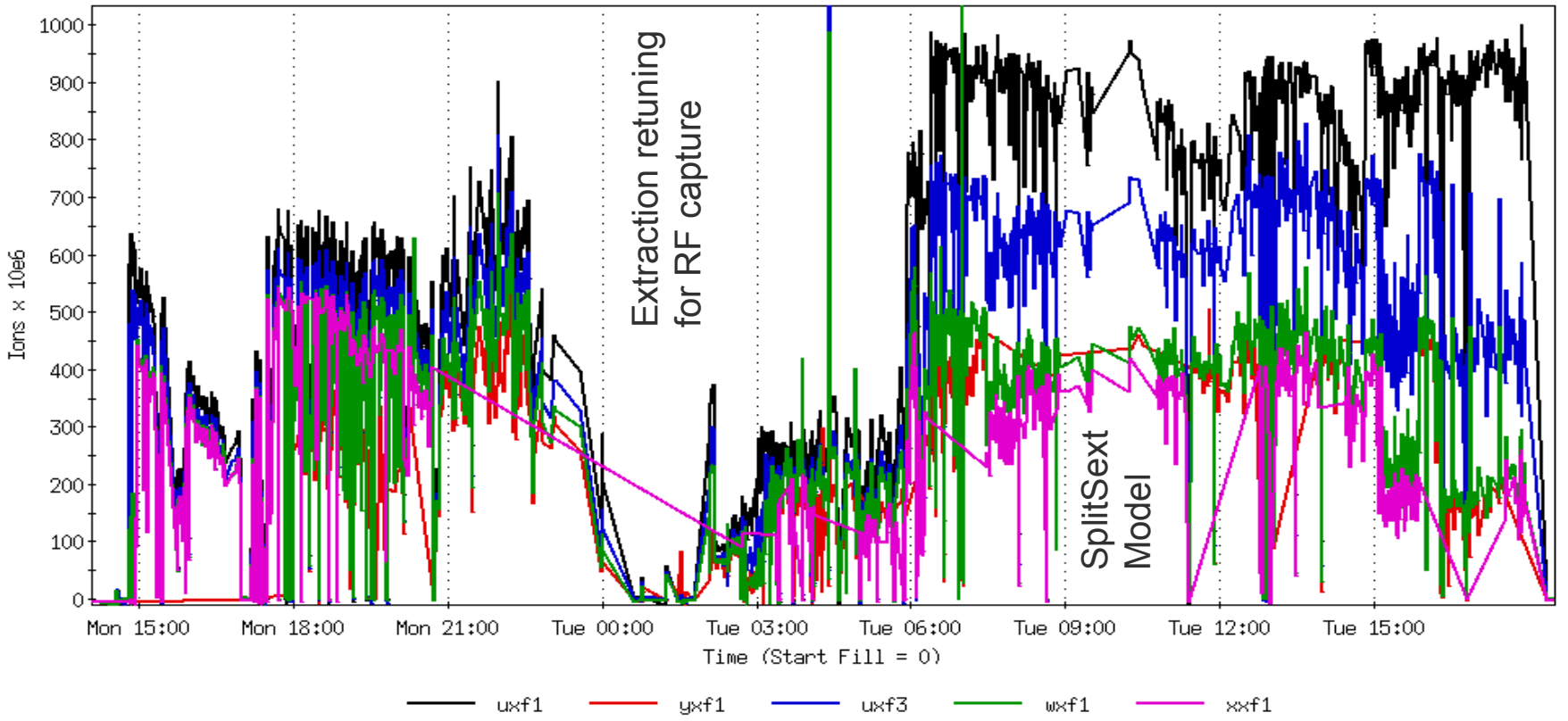
E=2.5 GeV/u Downramp Orbit Correction

- Even sliding bumps in arcs failed on downramp hysteresis
- Indicates that phase advance/cell is wrong: quad trans func
  - After hysteresis, orbit correction worked with some rescaling



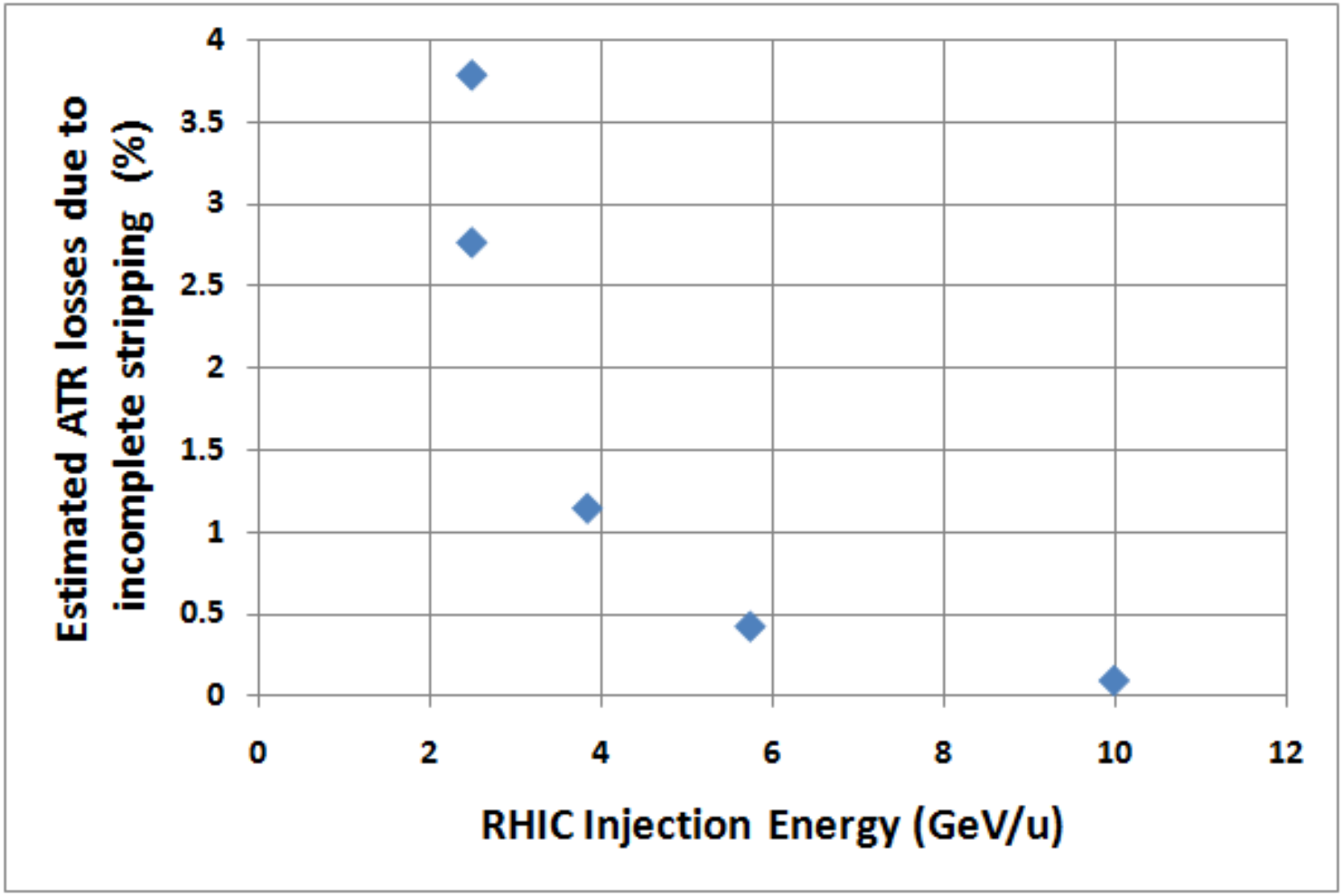


E=2.5 GeV/u ATR Tuning



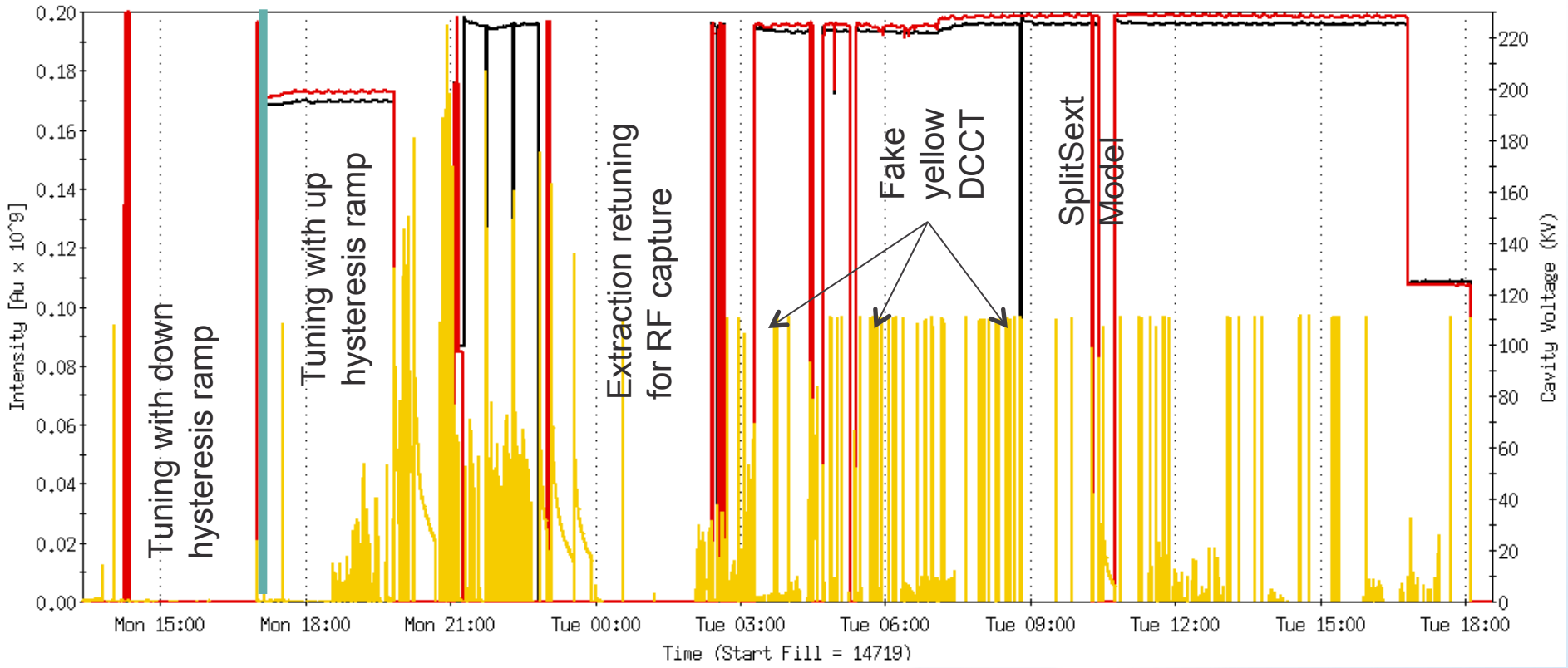
- Amazingly fast beam back to x/yxf1 (a handful of shots!)
- Retuning for RF capture was painful
- ATR efficiency can be quite good (5-10% stripping losses?)

ATR Stripping Efficiency



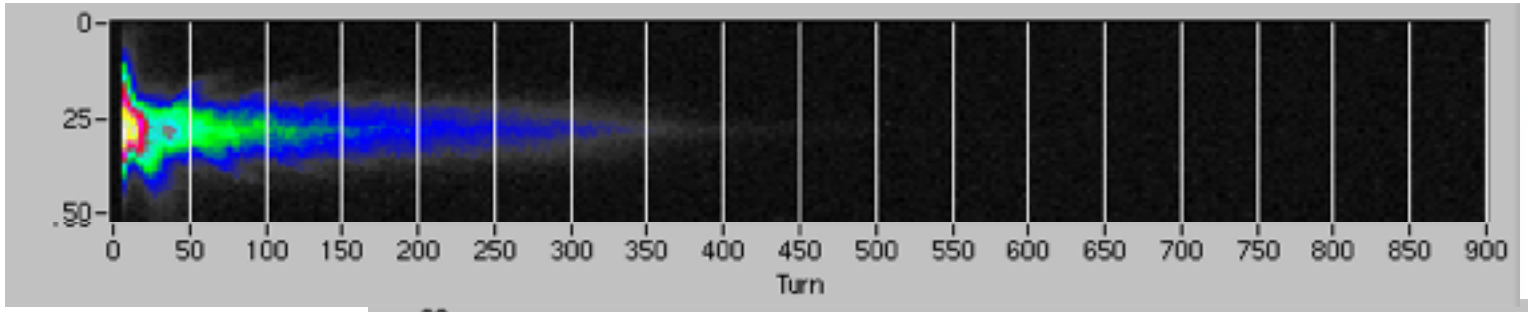
- Estimates from Peter Thieberger (49 mg/cm^2 Tungsten foil)
- Inefficiency 3x larger than 3.85 GeV/u, 30x larger than 10 GeV/u

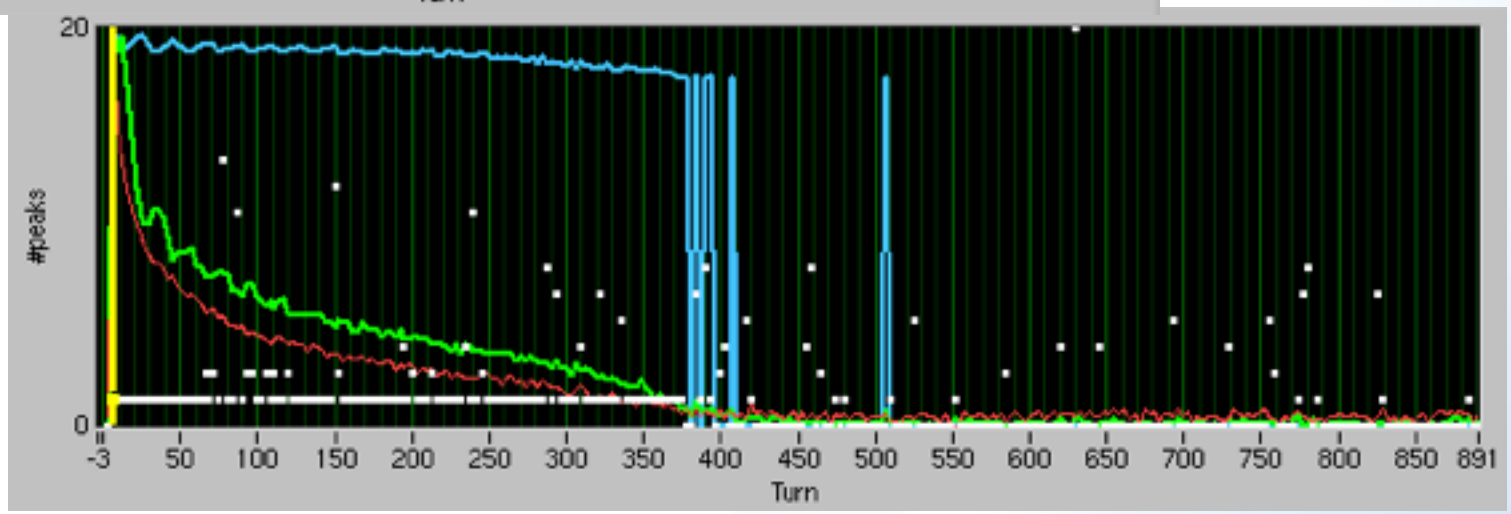
E=2.5 GeV/u Yellow Beam Currents



- No bunched beam achieved on yellow WCM
- Peak DCCT 2e8 unbunched, 6e7 “bunched”, 2.5e7 bunched
- Yellow had better unbunched, worse bunched behavior

E=2.5 GeV/u Yellow Injection

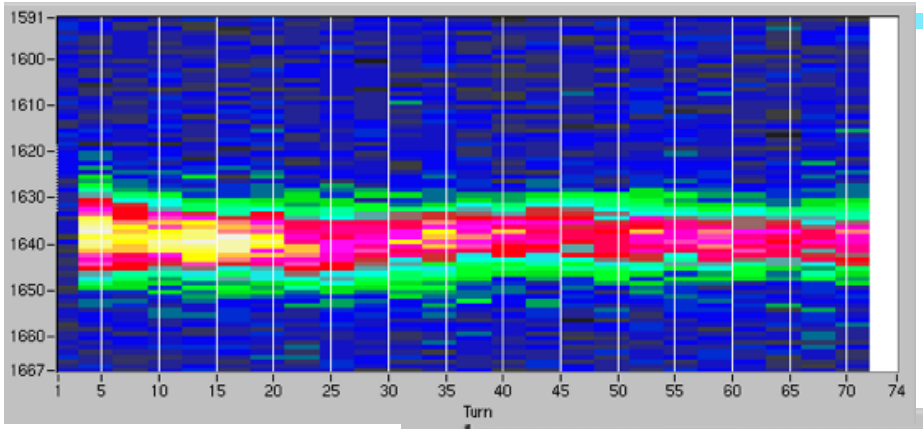


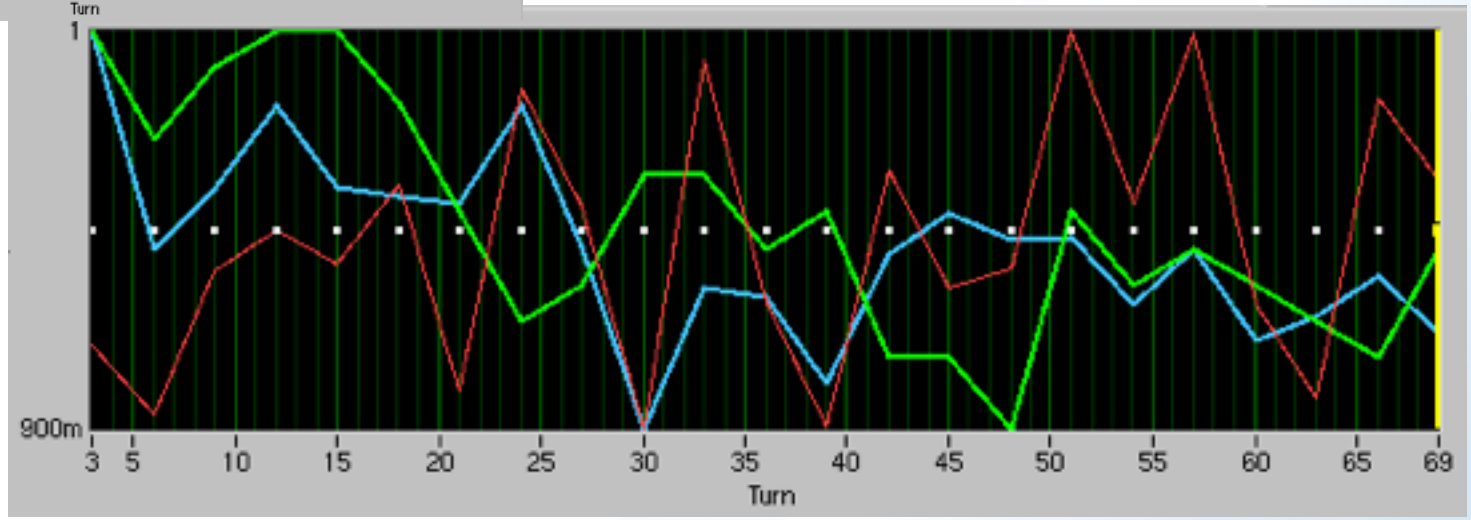


Sync period
1.7 kHz = 42 turns

- Scanned tunes, chromaticities by over 40 units
- Peak/total intensity still dropped x2 in ~50 turns, gone in 400
- RF on, 16:31 Tuesday afternoon

E=2.5 GeV/u Blue Injection

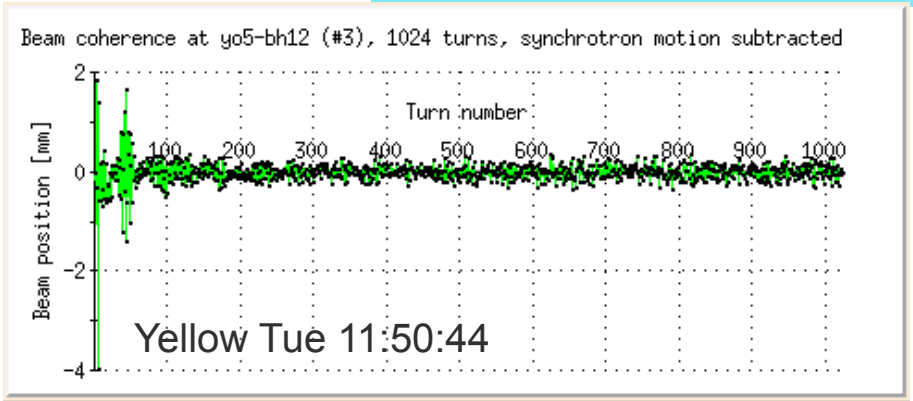


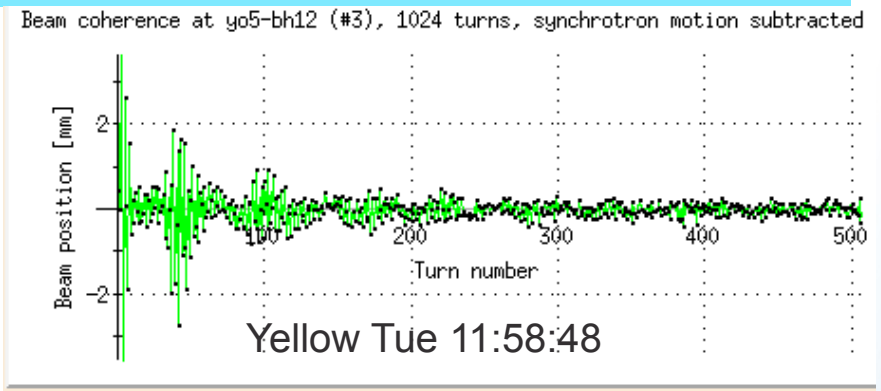


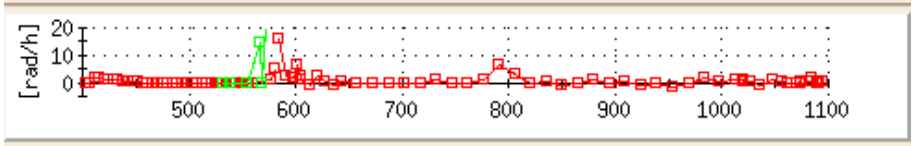
Sync period
1.7 kHz = 42 turns

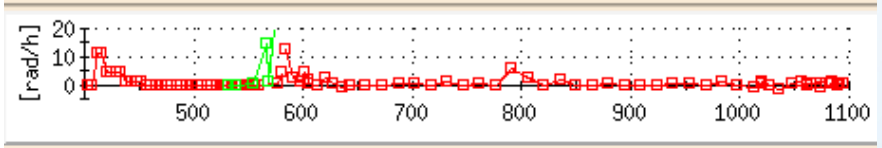
- Also scanned chromaticities by over 40 units
- Yellow peak and total intensity still dropped very quickly
- RF on, 15:10 Tuesday afternoon

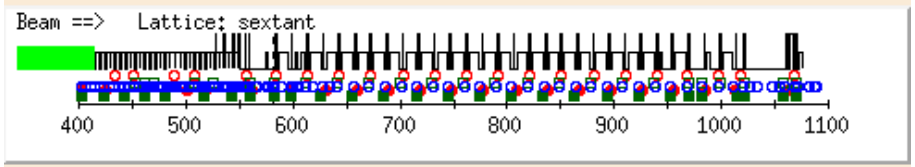
E=2.5 GeV/u TBT data

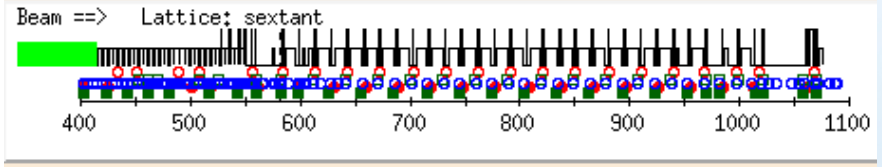




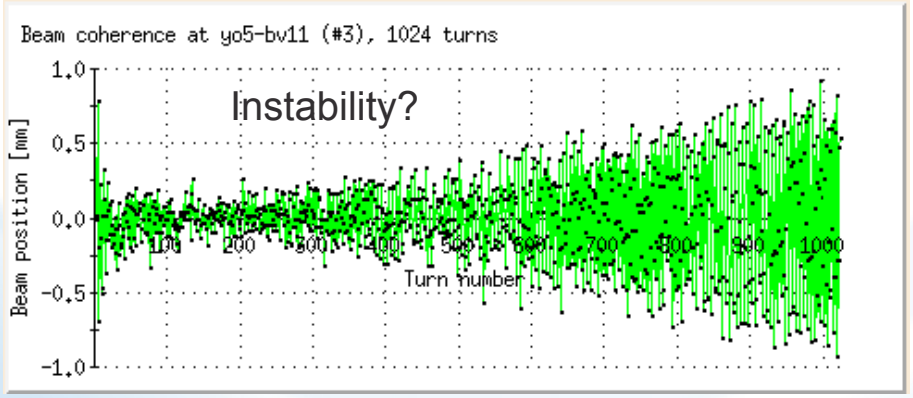




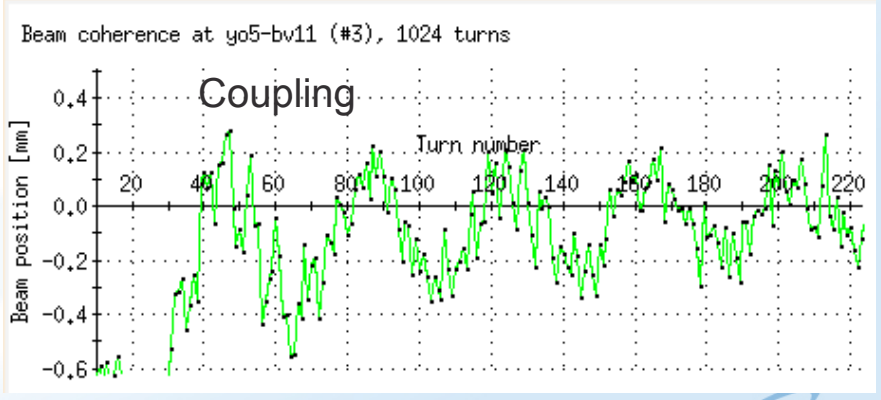




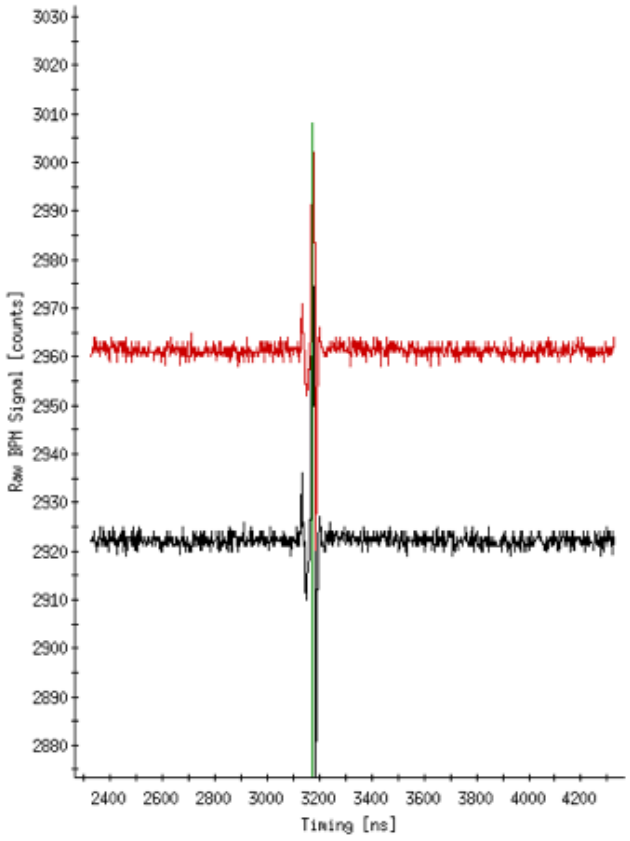
Vertical plane



Vertical plane



E=2.5 GeV/u Blue BPM Timing



Use	Show	BPM Name	Status	gateDelay	gateWidth	delayA	peakA	delayB	peakB
Use	–	b-g6-bhx	okay	8333.26	2000.00	548.83	3467.00	1195.31	3554.00
Use	–	b-g6-bvx	okay	8337.56	2000.00	1564.45	3614.00	1472.66	3580.00
Use	–	bo6-bh1	okay	643.82	2000.00	619.14	3027.00	156.25	2827.00
Use	–	bo6-bv1	okay	646.42	2000.00	97.66	2532.00	31.25	2696.00
Use	–	bo6-bh3	okay	562.76	2000.00	19.53	3837.00	1320.31	3628.00
Use	–	bo6-bv3	okay	555.21	2000.00	935.55	3798.00	162.11	3571.00
Use	–	bo6-bh3.1	okay	889.91	2000.00	984.38	2760.00	1210.94	2744.00
Use	–	bo6-bv3.1	okay	890.06	2000.00	1630.86	3159.00	386.72	2719.00
Use	–	bo6-bh4	okay	908.96	2000.00	1939.45	3006.00	1939.45	2833.00
Use	–	bo6-bv4	okay	1279.31	2000.00	1583.98	2669.00	1583.98	2620.00
Use	–	bo6-bv5	okay	1242.26	2000.00	1580.08	3296.00	1582.03	2898.00
Use	–	bo6-bh6	okay	1252.56	2000.00	1658.20	3488.00	1656.25	2706.00
Use	–	bo6-bh7	okay	1229.31	2000.00	1802.73	3701.00	1802.73	3674.00
Use	–	bo6-bv7	okay	1234.56	2000.00	1806.64	3564.00	1806.64	3564.00
Use	–	bo6-bh8	okay	1269.31	2000.00	1880.86	3164.00	1882.81	2933.00
Use	–	bo6-bv8	okay	1279.01	2000.00	1884.77	2839.00	1882.81	2854.00
Use	–	bo6-bv9	okay	2349.46	1000.00	612.30	3422.00	704.10	3754.00
Use	–	bo6-bh10	okay	2330.71	2000.00	1115.23	3326.00	1113.28	3062.00
Use	–	bo6-bv11	okay	2299.31	2000.00	537.11	2698.00	537.11	2787.00
Use	–	bo6-bh12	okay	2306.26	2000.00	542.97	3017.00	542.97	2930.00
Use	–	bo6-bv13	okay	2297.31	2000.00	544.92	2750.00	544.92	2647.00
Use	–	bo6-bh14	okay	2314.71	2000.00	623.05	2767.00	623.05	2991.00
Use	–	bo6-bv15	okay	2290.56	2000.00	771.48	3011.00	771.48	3346.00
Use	Show	bo6-bh16	okay	2328.26	2000.00	847.66	2981.00	845.70	3008.00
Use	–	bo6-bv17	okay	2315.31	2000.00	992.19	3009.00	992.19	2877.00

triggerSourceS bit settings:

BASELINE	WOOT	FLASH	X1	X10	OFFSET	CURVE	PEAK	INTERNAL	PROFILE	FIXEDTRG
0x400	0x200	0x100	0x080	0x040	0x020	0x010	0x008	0x004	0x002	0x001

- Peak intensity about 40-50 counts 1min after injection
- x10-x100 worse signal/noise than normal BPM operation
- No bunched signal visible in yellow ring 1min after injection

E=2.5 GeV/u Recommendations

- Evaluate apertures
  - Modify beam optics at abort aperture
  - Tracking with best guess at nonlinear model

- E=3.85 GeV/u (h=369) beam had physics running
  - Step down gradually (2-3 steps) to E=2.5 GeV/u
  - Deceleration not feasible (changing harmonic number)
  - Be sure AGS/ATR are canonical => better intensity
  - BUT: smaller experiment beam pipes next year
  - Likely that E=2.5 GeV/u is too low; how far can we go?